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Exoplanet Exploration Program Technology Plan

Appendix

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Exoplanet Technology Plan Milestones

A.1 Introduction

The purpose of this appendix is to guide near-term (1–5 year) technology development for future space observatories related to NASA's Exoplanet Exploration Program (ExEP), and in so doing to enable a mission capable of detecting and characterizing the spectra of Earth-like exoplanets and atmospheric signatures of life. By developing this same technology it should also be possible to enable missions of lesser scope whose science is nonetheless compelling and essential to understanding the birth and evolution of planetary systems and the conditions that lead to life in the Universe.

This document is an appendix to the *Exoplanet Exploration Program Technology Plan* [1]. It will be revised and updated yearly. Its scope is intended to focus and amplify the aspects of ExEP technology development that most impact the Decadal Survey's recommended *New Worlds Technology Development Program* and its future *New Worlds Mission*. It therefore places the greatest emphasizes on the development of starlight-suppression technology. Other technology, such as used for microlensing, astrometry, radial velocity and transit measurements are not covered. These methods infer the presence of planets without the use of starlight suppression by measuring changes in the intensity, spectrum, or relative angular position of stars. Although these methods are undoubtedly important to future progress in exoplanet science, a discussion of their future technology development is beyond the scope of this appendix.

NASA's Exoplanet Exploration Program supports activities that will contribute to the community-based selection and advancement of one or more exoplanet mission concepts to a high Technology Readiness Level (TRL). The Program will fund and facilitate experiments and analyses selected by NASA HQ through yearly solicitations to advance related technology, and provide support through the infrastructure, expertise, and test facilities that have been developed in prior years.

The programmatic goals of the Exoplanet Exploration Program along with the anticipated schedule and budget for technology development are described in section A.2. The science requirements and the technology priorities are described in section A.3. Details of future milestones for coronagraphs, external occulters, and interferometers are then given in sections A.4, A.5, and A.6 respectively.

A.2 Programmatic Goals and Constraints

The 2010 Decadal Survey in Astronomy and Astrophysics [2] recommended the creation of a *New Worlds Technology Development Program* to advance the technological readiness of the three primary starlight suppression architectures. That effort should continue through the first half of the coming decade, and be accompanied by an increased investment of ∼$4M/yr over current levels. The Survey further recommended that—if the scientific groundwork and design requirements were sufficiently clear—an architecture downselect should be made at mid-decade, and a significantly increased technology investment on the order of $100M–$200M over the latter half of the decade should be focused to prepare a mission concept based on this architecture for consideration by the 2020 Survey.

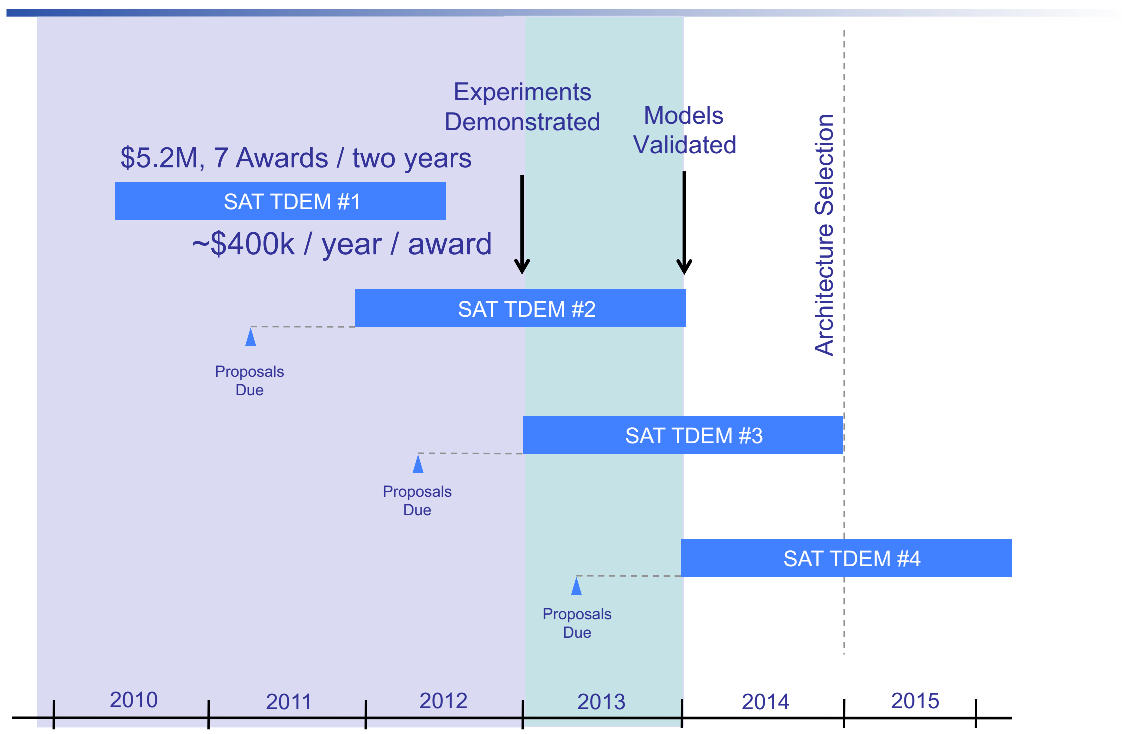

Figure A.1:
The anticipated funding and schedule available through the NASA ROSES Strategic Astrophysics Technology solicitation. The timeline is given in calendar years, with the 1st of January of each year denoted by the vertical bars. Proposals are due in March, and funding begins the following January. A notional schedule leading up to the architecture selection is illustrated that has some subset of experiments completed by January 2013 and the associated experimental models validated by January 2014. It is unlikely that such a demanding schedule will be realizable within the current budget allocations, and thus an architecture selection in 2015 may be heavily weighted on other factors such as the predicted mission scientific return, cost, and risk—if these have been studied in appropriate depth.

Table A.1: Funded Exoplanet Technology Research: TDEM 2009

PI	**Institution**	**Proposal Title**
Mark Clampin	NASA/GSFC	Visible Nulling Coronagraph Technology Maturation: High Contrast Imaging and Characterization of Exoplanets
Donald Figer	Rochester Inst. Tech.	A Photon-Counting Detector for Exoplanet Missions
Olivier Guyon	Univ. of Arizona	Phase-Induced Amplitude Apodization Coronagraphy Development and Laboratory Validation
N. Kasdin	Princeton University	Starshades for Exoplanet Imaging and Characterization: Key Technology Development
John Krist	JPL/Caltech	Assessing the Performance Limits of Internal Coronagraphs Through End-to-End Modeling
Martin Noecker	Ball Aerospace	Advanced Speckle Sensing for Internal Coronagraphs and Methods of Isolating Exoplanets from Speckles
John Trauger	JPL/Caltech	Advanced Hybrid Lyot Coronagraph Technology for Exoplanet Missions

NASA currently funds technology development through the Astrophysics Research and Enabling Technology (APRET) solicitation and the Technology Development for Exoplanet Missions (TDEM) component of the Strategic Astrophysics Technology (SAT) solicitation. APRET covers low TRL technologies and SAT-TDEM covers mid-range TRL technologies. This two-stage approach supports the advancement of technology envisaged by the Decadal Survey. TDEM tasks funded in 2009 are listed in Table A.1.

The long-term goal of exoplanet technology development is to enable a future mission by demonstrating selected key technologies relating to the most promising architecture. This effort must include the establishment of performance error budgets tied to flight requirements and experimental demonstrations that the error budgets, or key components of the error budgets, can be met. Furthermore, models must be validated that demonstrate that the physics of the limiting error sources in those experiments are understood well enough to reliably predict the performance of the flight mission.

The near-term goal of technology development is to mature the technology so that NASA might select the most promising architecture upon which to base continued efforts at the mid-decade, as articulated in the 2010 Decadal Survey.[1] This architecture would ideally have demonstrated several of its key milestones and moreover have developed a credible path forward to complete its remaining milestones by the end of the decade. The architecture selection would probably not be so specific as to select a particular instrument design, but it would limit the continuing effort to maturing the design and technology of the selected architecture.

The Exoplanet Program does not expect the technology for all architectures to be mature by the mid-decade. Figure A.1 illustrates a representative schedule with some subset of experiments and model validation being completed by January 2014. As indicated in the figure, the only

[1] Here the term "architecture" is used to distinguish between approaches used to design an exoplanet mission: coronagraph, external occulter, or interferometer. Note that for the purpose of this document a Visible Nulling Coronagraph is considered to be one of several possible implementations of an instrument for a coronagraph architecture.

future awards that provide an opportunity to influence a decision in 2014 are those beginning in January 2012 and 2013 (with proposal deadlines of March 2011 and 2012 respectively). Therefore the technology for each architecture will likely be incomplete and other factors will certainly be considered in the selection. These factors would include the predicted mission science-return, the anticipated cost, and overall risk—assuming that they had been studied by then in appropriate depth.

A.3 Science & Technology Objectives

A.3.1 Science Objectives

The science objectives that motivate technology development within the Exoplanet Exploration Program are focused on the discovery and characterization of *Earth-like* exoplanets. The principal goals are to detect and characterize Earth-like planets around nearby stars and to search for signs of habitability and life. For observations at optical and near-infrared wavelengths, the science objectives apply as formulated in 2006 by the Terrestrial Planet Finder Coronagraph (TPF-C) Science and Technology Definition Team (STDT) [3]. The first four objectives, describing terrestrial planet science, are as follows:

1. Directly detect terrestrial planets within the habitable zones around nearby stars or, alternatively, show that they are not present.
2. Measure orbital parameters and brightnesses for any terrestrial planets that are discovered.
3. Distinguish among planets, and between planets and other objects, through measurements of planet color.
4. Characterize at least some terrestrial planets spectroscopically, searching for absorption caused by O_2, O_3, H_2O, and possibly CO_2 and CH_4. It is highly desirable to measure Rayleigh scattering and photosynthetic pigments; such information may provide evidence of habitability and even of life itself.

Closely similar science objectives were also established for the Terrestrial Planet Finder Interferometer (TPF-I) for observations at mid-infrared wavelengths [4].

Up until now, the TPF science objectives have not been reformulated for the Program; they are well aligned with the priorities articulated in the 2010 Astrophysics Decadal Survey. They will nonetheless be reevaluated and revised as appropriate by the Exoplanet Program Analysis Group[2] (ExoPAG) by the spring of 2012. Until that time, the TPF science objectives [3, 4] are adopted by this plan.

[2] The ExoPAG serves as a community-based, interdisciplinary forum for analyses to NASA through the NASA Advisory Council (NAC), within which the ExoPAG Chair is a member of the Astrophysics Subcommittee. The ExoPAG is chartered with providing analysis to the NAC Astrophysics Subcommittee that includes the science objectives for potential future missions in the Exoplanet Exploration Program.

A.3.2 Performance Requirements

The TPF science objectives have been used to derive the required starlight rejection, angular resolution, inner working angle, sensitivity, bandwidth, and corresponding error budgets for the TPF missions. They can be equally applied to deriving performance requirements for a future *New Worlds Mission*.

The key instrument performance requirement is the ability to suppress starlight to a level where the detection of Earth-like planets becomes possible. This implies a performance level enabling contrasts of 10^{-10} at visible wavelengths, or starlight suppression of 10^{-6}–10^{-7} at mid-infrared wavelengths. Details of the optical-wavelength performance requirements are given in Table A.2.

These starlight suppression requirements hold true irrespective of the mission architecture. The technology Milestones described in the TPF technology plans [5, 6] remain valid. In those plans, demonstrated laboratory performance within an order of magnitude of the flight requirement—10^{-9} at visible wavelengths and 10^{-5}–10^{-6} at mid-infrared wavelengths—was deemed sufficient to proceed to Phase A.[3] These performance requirements are therefore also adopted by this plan.

Table A.2: Optical-Wavelength Performance Requirements

Metric	**State of the Art**	**Requirement**
Design	4th order mask	
Contrast	5×10^{-10}, 10% bandwidth 3×10^{-9}, 20% bandwidth	$\leq 1 \times 10^{-10}$
Contrast stability		$\leq 1 \times 10^{-11}$ / image
Inner working angle	$4\lambda/D$	$2\lambda/D$–$3\lambda/D$
Model validation	Errors predicted to $\sim 10^{-9}$	Errors predicted to 10^{-11}

A.3.3 Technology Priorities

The recommendation by the Decadal Survey was to continue to pursue the development of coronagraph, external occulter, and interferometer technologies to allow an architecture downselect by the mid-Decade. Nevertheless, at its February 2011 meeting, the Astrophysics Subcommittee (ApS) of the NASA Advisory Council endorsed a suggestion from the Exoplanet Exploration Program Analysis Group (ExoPAG) that, for both cost and technical readiness reasons, infrared interferometry should be of lower priority as the basis for the Decadal Surveys New Worlds Mission than either of the coronagraph or starshade architectures. NASA Headquarters and the Exoplanet Exploration Program acknowledge this guidance from the ApS, and will take it into consideration in managing our New Worlds Technology Development portfolio. Note: Visible Nulling Coronagraphs, though based on interferometer technology, are here considered to be an instrument design for a coronagraph architecture, equal in priority with other coronagraph instrument designs.

[3] This assumption may need to be revisited. Requiring performance to be only within an order of magnitude of flight requirements is inconsistent with the goal that a technology achieve TRL 5 by 2020.

The highest priority technology demonstrations for all architectures are the following:

1. Experimental demonstrations that the necessary starlight suppression is achievable;
2. The validation of models and error budgets that demonstrates the physics of starlight suppression including the dominant sources of instrument noise are understood within the accuracy required for on-orbit performance prediction.

Demonstrations that emphasize approaches that provide high-sensitivity and a small inner working angle are particularly valued as they may greatly increase the science return from a mission.

The above demonstrations by themselves take precedence over any unrelated technology efforts. Unrelated topics will be specifically excluded from future SAT-TDEM calls where appropriate. When first solicited in February 2009 and again in February 2010, TDEM had no specific technologies excluded, although suborbital programs were not solicited due only to a limited budget.[4] The technologies that were specifically excluded in the 2010 SAT-TDEM call[5] were cited to focus the effort in response to the 2010 Decadal Survey. The exclusions were the following: (1) detector technology; (2) mirror technology (with the exception of adaptive systems); (3) telescope assembly technology; (4) sunshields and isothermal control; (5) propulsion systems; (6) vibration isolation systems; (7) spacecraft pointing control; and (8) formation flying technology.

The following sections outline the Milestones for coronagraphs, external occulters, and interferometers. In the case of coronagraphs, the detailed high-level milestones for pre-Phase A have already been defined; these are adopted for this plan. In the case of external occulters, a detailed plan has not previously been adopted by the Exoplanet Program. The milestones for external occulters are therefore not presented in detail; the major subject areas are listed in bullet form, with the understanding that quantitative milestones will be developed by PIs themselves. The next revision of this appendix will include formal milestones for the external occulters, as are given here for the coronagraphs. The milestones for interferometry architectures are also described.

A.4 Coronagraph Milestones

There are currently several approaches to the design of coronagraph instruments. Such instruments may include implementations of intensity masks [7], phase masks [8], phase-induced amplitude apodization [9], visible nulling coronagraphs [10], or hybrid designs [11].

The state of the art demonstrated in the lab is summarized in Fig. A.2. Most notable amongst these results is a contrasts of 5×10^{-10} with a 10% bandwidth at $4\lambda/D$ achieved through the use of 4^{th} order intensity masks [12]. Using similar masks, contrasts of 3×10^{-9} have been achieved with a 20% bandwidth at $3\lambda/D$ [13]. Models exist that match these results, although they have not yet been formally validated. The other results plotted in Fig. A.2 are described later in the text.

Four high-level technology milestones were developed for the Terrestrial Planet Finder Coronagraph.[6] The milestones below are paraphrased from the TPF-C Technology Plan [6] and Milestone documents [12, 14, 15]. The first milestone demonstrates the feasibility of the technique. The

[4]The second solicitation, making TDEM part of the new SAT solicitation, was withdrawn to accommodate changes in the NASA Astrophysics Division's planned budget outlined in the President's fiscal year 2011 budget request.

[5]Released 12 February 2010 as part of the 2010 ROSES call, with proposals due 25 March 2011.

[6]The milestones were numbered 1, 2, 3A and 3B

second demonstrates that it is applicable over a representative science band. The third demonstrates that the physics models are well understood and the known sources of noise are controlled, thus validating the error budget for the most problematic sources of system degradation. The fourth demonstrates through observatory simulation, combined with experimental results, that the mission could achieve its stated science goals. These milestones are progressive and sufficiently generalized to be applicable to any optical coronagraph mission concept. These are the most significant high-level milestones to be accomplished in pre-Phase A.

1. Narrow-band Starlight Suppression. Demonstrate monochromatically the technology for Earth-like planet detection by optical starlight suppression to a level within an order of magnitude of the required flight performance. Using monochromatic light at an optical wavelength in the intended science band, a contrast of less than 1×10^{-9} must be achieved in a target dark hole whose inner working angle is representative of the flight mission. The demonstration must be repeated on three separate occasions.[7]

2. Broad-band Starlight Suppression. Demonstrate with broadband light the technology for Earth-like planet detection by optical starlight suppression to a level within an order of magnitude of the required flight performance. Using broadband light with a fractional bandwidth $\Delta\lambda/\lambda \geq 10\%$ centered at an optical wavelength in the intended science band, a contrast of less than 1×10^{-9} must be achieved in a target dark hole whose inner working angle is representative of the flight mission. The demonstration must be repeated on three separate occasions.[8]

3A. Model Validation of Starlight Suppression. Demonstrate that starlight suppression performance predictions from high-fidelity optical models of experiments, using measured data on specific testbed components, are consistent with actual measured results on the testbed. The correlation of model predictions with experimental testbed results thus validates models at a baseline contrast ratio of better than 1×10^{-9} (goal 1×10^{-10}). The measurement to be evaluated is the comparison between the contrast predicted by the model and the contrast achieved in the experiment. In each open loop test, the perturbation to be introduced shall change the model contrast from nominal by at least $s \times 10^{-9}$, where s is the step number (1, 2, 3) and shall be in agreement with the model prediction to 1×10^{-9}. In closed loop tests, the change in model contrast is evaluated after the wavefront control system (WFCS) has operated. Closed loop perturbations shall change the post-WFCS model contrast by at least 2×10^{-9} from nominal. Multiple step closed loop tests do not necessarily involve progressive delta contrast steps. Broadband light must be used with a fractional bandwidth $\Delta\lambda/\lambda \geq 10\%$ centered at an optical wavelength in the intended science band. The contrast metrics must be demonstrated in a target area representative of the flight mission.

3B. Demonstrate, using the modeling approach validated against experimental results (above) combined with appropriate telescope models and the current mission error budget, that a coronagraph could achieve a baseline contrast of 1×10^{-10} over the required optical bandwidth necessary for detecting Earth-like planets, characterizing their properties and assessing habitability.[9]

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[7] Milestone #1 completed for 4th order masks, 10 July 2006 (Trauger, Kern, and Kuhnert 2006)

[8] Milestone #2 completed for 4th order masks, 8 August 2008 (Kern, Kuhnert, and Trauger 2008)

[9] This is a modeling activity that may require the development of a Design Reference Mission as part of a larger mission study. All the supporting experimental work would have been completed prior to this activity.

Progress toward achieving the above high-level milestones could be marked by milestones in other key technologies. Related activities could include for example (a) the development of special-purpose optics such as image-plane masks or apodizing optics, (b) improved wavefront sensing and control methods, (c) more efficient modeling algorithms.

Future milestones in Phase A would include those related to structural, thermal, and spacecraft technology demonstrated at the component, subsystem, and system level. A key milestone in this regard would be a precision structure stability demonstration.

A.4.1 Progress and Plans

Band-limited Lyot Masks

Milestones 1 and 2 were completed by the TPF-C Pre-Project for an instrument design employing a linear 4th-order band-limited mask [12, 14]. This mask used an intensity-only design.

No further development of masks of this exact same design is anticipated because its performance degrades at larger bandwidths and smaller inner working angles. Subsequent work on masks of this type, described below, has focused on an improved *hybrid* design that includes a dielectric layer to compensate for small phase errors induced by the metallic intensity mask. Nonetheless, band-limited Lyot masks that were developed by the TPF-C Pre-Project are being used in trials for coronagraph model validation, as described on the page 10.

Band-limited Hybrid-Lyot Masks

The milestone objective is to demonstrate, using linear hybrid Lyot masks, a calibrated coronagraph contrast of 1×10^{-9} at angular separations of $3\lambda/D$ and greater in a single 720–880 nm (20%) spectral band. This milestone is more ambitious than Coronagraph Milestone 2, because it attempts a broader bandwidth.

Experiments with hybrid masks in the High Contrast Imaging Testbed (HCIT) in 2010 achieved a contrast of 2.7×10^{-9} with a bandwidth of 20% at an inner working angle of $3\lambda/D$. This level of performance is comparable to results from hybrid masks obtained in 2009. The limiting factor was identified as an error in the mask design and fabrication, and new masks are being fabricated with the goal of testing them when the HCIT again becomes available in Q4 of FY2011. Future work may include operation in two shorter wavelength bands and the implementation of circular hybrid masks.

Phase-Induced Amplitude Apodization

The milestone objective is to demonstrate using Phase-Induced Amplitude Apodization (PIAA) a baseline contrast averaging 1×10^{-9} between a $2\lambda/D$ inner working angle and a $4\lambda/D$ outer working angle, in monochromatic light at a wavelength in the range of 400 nm $\leq \lambda \leq$ 900 nm. This goal is identical to Coronagraph Milestone 1. Supporting work toward this goal is being conducted at the NASA Ames Coronagraph Experiment (ACE) and the JPL/Caltech High Contrast Imaging Testbed (HCIT).

The research at ACE is conducted using a thermally stabilized enclosure, permitting initial validation (TRL 1–4) of PIAA and related technologies that can then be validated at higher TRL levels (TRL 4+) using the vacuum facility of the HCIT.

Experiments at ACE in 2010 achieved a contrast of 5.4×10^{-8} using a lens-based design and 3.0×10^{-7} using a paired-mirror system, both in monochromatic light at an inner working angle

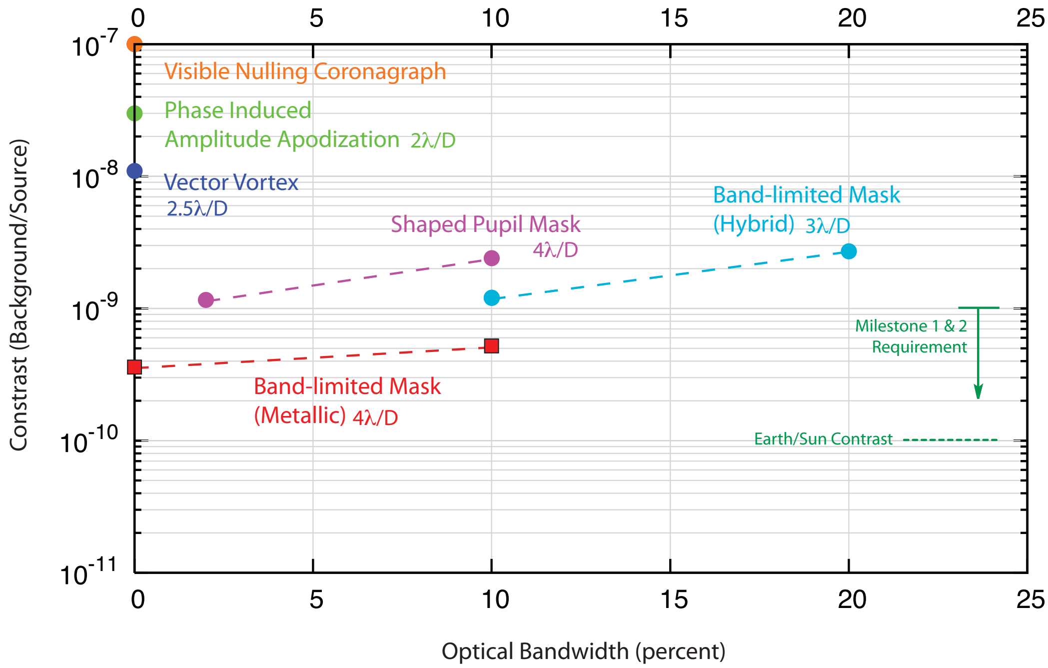

Figure A.2: Demonstrated coronagraph contrast as a function of bandwidth. This plot summarizes results described in the text. Results reported by PIs or found in the published literature are denoted by the filled circles. Milestone results are denoted by the filled squares.

of $2\lambda/D$. Experiments in the HCIT in 2010 achieved a contrast of 3×10^{-8} with paired-mirrors in monochromatic light. Diagnostic tests will be conducted at each facility to identify the limiting noise sources. Infrastructure within the JPL Micro-Arcsecond Metrology (MAM) vacuum chamber is being upgraded to accommodate PIAA experiments so that they could run concurrently with Lyot mask experiments in the HCIT. A new low-order wavefront sensor will be implemented to improve the pointing required at small inner working angles and may be the subject of parallel milestone work.

Vector Vortex Coronagraph

Experiments in the HCIT in Q2 of FY2011 using monochromatic light achieved a mean contrast of 1.1×10^{-8} at a working angle of $2.5\lambda/D$. These experiments were not undertaken as a formal milestone, but represent progress toward Coronagraph Milestone 1. This advance is an improvement in performance of an order of magnitude over prior results obtained in 2009.

Improved vector vortex masks are being developed. Future plans would include Coronagraph Milestone 1, although this is contingent upon continued funding and access to the HCIT, which is not guaranteed in FY2011.

Visible Nulling Coronagraph

The milestone objective is to demonstrate that the Visible Nulling Coronagraph (VNC) can achieve and hold a contrast of 1×10^{-8} (goal less than 1×10^{-9}) at a $2\lambda/D$ inner working angle at a visible wavelength centered in a narrowband filter of spectral bandpass $< 1\%$. This represents a preliminary step toward Coronagraph Milestone 1.

Experiments with single-fibers have yielded null depths of 1×10^{-7} [16]. In separate experiments at both JPL/Caltech and NASA/GSFC, the necessary wavefront sensing and control has been demonstrated to phase the coronagraph. New coherent fiber bundles have been acquired and successfully tested. Results to date suggest that contrasts of 10^{-8} and 10^{-9} are achievable [10, 17], and experiments are now underway at NASA/GSFC with the goal of attaining the above milestone in Q3 of FY2011.

Shaped Pupil Masks

Vacuum experiments with shaped-pupil masks in the HCIT have yielded contrasts of 1.16×10^{-9} with a 2% bandwdith and 2.4×10^{-9} with a 10% bandwdith, both at inner working angles of $4\lambda/D$ [18].

Ongoing work being undertaken at Princeton University includes the implementation of a hybrid design that combines shaped pupils with a pair of deformable mirrors with the goal of enabling a higher throughput at a smaller inner working angle [19, 20].

Model Validation of Band-limited Lyot Mask Coronagraphs

The milestone objective is to validate coronagraph performance models using the HCIT, as described in Coronagraph Milestone 3A.

Initial experiments were undertaken for a period of two weeks in Q2 of FY2011 using a band-limited Lyot mask. Results were encouraging, but the trials did not yet demonstrate model agreement at milestone levels. Future plans would include the completion of Coronagraph Milestone 3A, with work to recommence in FY2012 contingent upon funding and access to the HCIT.

Efficient Coronagraph Optical Modeling

The milestone objective is to identify, implement in code, and verify efficient numerical methods for representing wavefront modification by the Hybrid Band-Limited Coronagraph (HBLC), the Vector Vortex Coronagraph (VVC), and the Phase-Induced Amplitude Apodization (PIAA) coronagraph that are accurate to 1% or better relative to the mean field contrast for contrasts down to 10^{-10}. This represents a related activity because it does not currently include experimental validation of the models, as required in Coronagraph Milestone 3A. This work is being conducted at JPL/Caltech.

The first phase of work, to validate the code against known reference solutions, has been completed for the Vector Vortex and PIAA models, but not yet for band-limited masks. When the first phase is completed, work will then proceed to a second phase to predict coronagraph performance with realistic wavefront errors.

Rapid Wavefront Sensing and Control

The milestone objective is to use coherent speckle detection methods, and demonstrate the capability to measure speckles of about 1×10^{-8} contrast with uncertainty, stability, and repeatability of 20% in intensity and 1 radian in phase with 90% statistical confidence, in a window at least $2 \times 2\lambda/D$ wide at $< 10\lambda/D$ from the star, in one spectral band of width $> 10\%$, with a uniform incoherent back-ground of at least 1×10^{-8} in the area covered by the PSF. The goal is to provide a faster servo loop to improve the stability of measurements requiring long integration times. This represents a related activity which may improve the stability of experiments represented by Coronagraph Milestones 1, 2, and 3A.

This work is being led by Ball Aerospace and Technology Corporation. Experimental work has not yet begun, but is anticipated to begin in early FY2012 using the HCIT.

A.5 Starshades Milestones

There are two similar approaches to the designs of external occulters currently being studied, differing by whether an analytical petal shape is used [21] or whether it derives from a mathematical optimization [22].

Laboratory tests have demonstrated contrasts of 2.6×10^{-7} at the inner working angle, in radially averaged data, using subscale silicon-etched external occulter masks [23]. Ongoing research is investigating various aspects of the manufacturability of petals. Several options for deployment are also being evaluated [24, 25, 26].

The likely subject areas for external occulter milestones are listed below. In this list, the first three milestones are related to the design and fabrication of external occulters. The fourth milestone is a demonstration of deployment. The fifth demonstrates guidance, navigation, and control of external occulters. The sixth is analogous to the final pre-Phase A milestone for coronagraphs: a demonstration that the on-orbit performance is achievable based upon a well-grounded understanding of the error budget, backed by the necessary laboratory results.

- Petal manufacturing. Demonstrate that a single petal can be manufactured to the design tolerances. A representative set of manufacturing tolerances shall be demonstrated that derive from known error budget allocations.
- Petal thermal deformation. Demonstrate that thermal deformations of a petal can be controlled within the budgeted tolerances for anticipated flight conditions of science operations.
- Edge scatter of sunlight. Demonstrate with a baseline external occulter design that the brightness of light scattered from the external occulter edges would be less than the brightness of exozodiacal light.
- Petal deployment. Demonstrate that the petals of a external occulter can be deployed to within the budgeted tolerances.
- Formation flying. Demonstrate that the guidance, navigation and control of a external occulter can be achieved with regard to the budgeted tolerances of its lateral alignment with its telescope.
- Demonstrate, using the modeling approach validated against experimental results combined with appropriate telescope models and the current mission error budget, that a external occulter could achieve a baseline contrast of 1×10^{-10} over the required optical bandwidth necessary for detecting Earth-like planets, characterizing their properties and assessing habitability.

Future milestones in Phase A would include additional topics related to formation flying. This would include demonstrating the required dynamical stability of the petals in flight and related spacecraft technology demonstrated at the component, subsystem, and system level.

A.5.1 Progress and Plans

Starlight suppression experiments

Starlight suppression experiments using scaled starshades have produced contrasts of 2.6×10^{-7} at the starshade mask's inner working angle [23], and features as faint as 5×10^{-10} have been detected outside the inner working angle. These experiments are designed to measure the starshade's shadow at the same Fresnel number as would be used in an actual flight-system, but not at the same inner working angle. The masks are centimeters in diameter and placed at tens of meters from the detector. Future efforts would depend on continued funding.

Precision Petal Manufacturing

The milestone objective is stated as follows. On a single full-scale petal made of fight-like materials, measure the edge position relative to a fiducial origin at a sufficient number of locations along the edge. Using optical modeling tools, verify that the predicted mean contrast in the image plane from a uniform field propagated past an occulter with petals of the measured shape in an annulus of width equal to the full-width half-max of the telescope point spread function at the smallest inner working angle is 3×10^{-10} or better, the allocated contrast to static errors. Repeat the measurements and analysis a sufficient number of times to give 95% confidence that the predicted contrast is correct.

This work is being led by Princeton University. The experimental and modeling work is anticipated to begin in late FY2011 and continue through FY2012.

A.6 Interferometer Milestones

Interferometry technology will ultimately provide higher angular resolution and thus the ability to detect and characterize a larger sample of exoplanets than is possible with either coronagraph or external occulter architectures. A summary of interferometer milestones is given below. Milestone 1 is a demonstration of adaptive correction of wavefront errors necessary for to attain deep null depths. Milestone 3 is a demonstration of starlight suppression over a broad bandwidth using a two-element interferometer. Milestone 4 is a system demonstration using a four-element interferometer. Milestone 5 demonstrates the techniques of spectral fitting, which is the final step in starlight suppression necessary to detect exoplanets at mid-infrared wavelengths. These starlight suppression milestones are equally applicable to connected-structure and formation-flying concepts. Milestone 2 is a laboratory demonstration of formation-flying guidance, navigation & control.

1. Using the Adaptive Nuller, demonstrate that optical beam amplitude can be controlled with a precision of $\leq 0.2\%$ rms and phase with a precision of ≤ 5 nm rms over a spectral bandwidth of $> 3\ \mu$m in the mid IR for two polarizations. This demonstrates the approach for compensating for optical imperfections that create instrument noise that can mask planet signals. This goal is consistent with starlight suppression of 1×10^{-5}.

2. Using the Formation Control Testbed (FCT) as an end-to-end system-level hardware testbed, demonstrate that a formation of multiple robots can autonomously initialize, maneuver and operate in a collision free manner. A key maneuver, representative of TPF-I science will be demonstrated by rotating through greater than 90° at ten times the flight rotation rate while maintaining a relative position control to 5 cm 1σ per axis. This is the first step in a

full validation of the formation control architecture and algorithms and the testbed models developed by the Formation Algorithms & Simulation Testbed while physically demonstrating a scaled version of the approach to achieving the angular resolution required for the detection of terrestrial planets.

3. Using either the Adaptive Nuller or the Achromatic Nulling Testbed, demonstrate that mid-infrared light in the 7–12 μm range can be suppressed by a factor of $\geq 10^5$ over a waveband of $\geq 25\%$. This demonstrates the approach to broadband starlight suppression (dimming of light across a range of wavelengths) needed to characterize terrestrial planets for habitability. Flight-like nulls are to be demonstrated at room (non-flight) temperature.

4. Using the Planet Detection Testbed, demonstrate detection of a simulated planet signal at a star/planet contrast ratio of $\geq 10^6$. This demonstrates that several opto-mechanical control loops can be integrated and operated in a testbed configuration that includes the principal functional blocks of the flight instrument. These functional blocks include fringe tracking, pathlength metrology, beam shear and pointing control, 4-beam combination and phase chopping. Success shows that an instrument can be operated with a stability representative of flight requirements and within about an order of magnitude of the contrast that permits the detection of the signal from an earth-like exoplanet in the habitable zone around a nearby star.

5. Using the Planet Detection Testbed demonstrate the starlight suppression technique of spectral fitting. The spectral fitting technique uses measurements which can be obtained from a broad band of nulled wavelengths to detect and remove the effect of opto-mechanical disturbances on the null, thereby effectively suppressing the starlight by another factor of ten.

Milestones 1, 2, 3, and 4 were completed by the TPF-I Pre-Project.

Laboratory demonstrations of interferometric nulling at mid-infrared wavelengths have been successful at reaching the performance needed to support a flight mission. The Milestone 1 demonstration of phase and intensity control of fringes was demonstrated at the required level [27]. The Milestone 3 demonstration of starlight suppression of 1×10^{-5}, was demonstrated with a 30% bandwidth [28], at such a level that the planet signal would be dominated by exozodiacal light, not starlight. The Milestone 4 system demonstration using two pairs of interferometers achieved contrasts of 1.65×10^{-8} in the lab using laser sources, with an experimental subtraction of noise using infrared chopping and averaging [29, 30].

Work in progress on Milestone 5 is described below in section A.6.1. In addition, further work is needed to demonstrate the same noise subtraction techniques over broader bandwidths and in a cryogenic environment. This would necessitate the testing of cryogenic mid-IR single-mode fibers, deformable mirrors, adaptive nullers, and more comprehensive system testing at liquid nitrogen temperatures.

Whereas a coronagraph architecture would be an extrapolation of existing space telescopes designs, it is very likely that an interferometer would have no precursor in space—whether it be a connected-structure design or a formation-flying mission. The Milestone 2 demonstrations of formation flying were successfully completed in a lab environment with hardware in the loop and 5-degrees of freedom for the two controlled satellites [31, 32]. Nonetheless, the technology development for a formation flying interferometer may follow a path that includes one or more technology space missions prior to its full implementation.

A.6.1 Progress and Plans

Spectral Fitting and Planet Detection

The milestone to be demonstrated is Milestone 5, above, using the Planet Detection Testbed.

Work has been underway in FY2011 to modify the Planet Detection Testbed and upgrade a broad-band mid-infrared detector for use with this milestone. The goal is to complete the stated milestone. Progress is contingent upon continued funding, which is not guaranteed beyond Q3 of FY2011. This milestone would complete the suite of room-temperature starlight suppression experiments that had been planned for mid-infrared interferometry.

A.7 Other Technology Milestones

Avalanche Photodiode Arrays

The Milestone to be demonstrated is a measurement of the performance of a photon-counting 256×256 Geiger-Mode Avalanche Photodiode (GM-APD) focal plane array after radiation exposure. The array is designed to provide zero read-noise, ultra-high dynamic range, and highly linear response. The following characteristics are to be measured: dark current, intrapixel response, total quantum efficiency, afterpulsing, persistent charge, and crosstalk. The measurements will be made before and after 50 krad (Si) $\sim$60 MeV proton irradiation. Important performance parameters include read noise, dark counts, and total quantum efficiency. This work is being conducted through the Rochester Institute of Technology.

This effort is a demonstration of new detector technology that may greatly improve the science throughput of coronagraph and starshade mission concepts. Its development, funded prior to the SAT-TDEM exclusion of detector technology in the 2010 solicitation, is subject to the same milestone process and review as other milestones described in previous sections.

Future work, subject to continued funding, would include the performance validation of focal plane arrays with a larger number of pixels (1024×1024 vs 256×256) and a higher fill-factor, along with additional radiation testing.

A.8 Summary

The 2010 Astrophysics Decadal Survey recommended the creation of a technology development program for a potential future exoplanet mission to mature starlight-suppression technology for the detection of spectra of Earth-like exoplanets. The Exoplanet Exploration Program is supporting a community-based process to help NASA Headquarters select a single architecture before 2015, and to mature the selected concept for recommendation in the 2020 Decadal Survey. This appendix serves to guide technology development toward that goal by specifying the technology milestones that each architecture must address in Pre-Phase A.

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